

REINVENTING THE DESIGN PROCESS: TEAMS AND MODELS

Stephen D. Wall
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena CA 91109 USA
(818) 354-7424
swall@mail1.jpl.nasa.gov

ABSTRACT

The future of space mission designing will be dramatically different from the past. Formerly, performance-driven paradigms emphasized data return with cost and schedule being secondary issues. Now and in the future, costs are capped and schedules fixed—these two variables must be treated as independent in the design process. Accordingly, JPL has redesigned its design process.

At the conceptual level, design times have been reduced by properly defining the required design depth, improving the linkages between tools, and managing team dynamics. In implementation-phase design, system requirements will be held in crosscutting models, linked to subsystem design tools through a central database that captures the design and supplies needed configuration management and control. Mission goals will then be captured in timelining software that drives the models, testing their capability to execute the goals.

Metrics are used to measure and control both processes and to ensure that design parameters converge through the design process within schedule constraints. This methodology manages margins controlled by acceptable risk levels. Thus, teams can evolve risk tolerance (and cost) as they would any engineering parameter. This new approach allows more design freedom for a longer time, which tends to encourage revolutionary and unexpected improvements in design.

INTRODUCTION AND SUMMARY

Engineering design processes are undergoing tremendous change in the 1990s. Cost and schedule consciousness, especially in the field of space mission design, has led to several initiatives to produce fundamental process change. The NASA Administrator has recently challenged NASA centers and their contractors to lead US industry in this revolution. The response to this challenge has led to fundamental redesign of the space mission design process [1], and work has begun to specify an underlying architecture [2].

In this paper we review a concept for revolutionary change to the space mission design process. At the conceptual design level, the basics of this process are installed and in routine use. Metrics based on more than

three years' performance are presented and discussed. This same basic process is now being installed at the implementation phase design level. We describe its model-driven design infrastructure, which uses a central database for design capture and configuration management, and its team-based design process. A simple model predicts savings in design time that can be realized.

OVERVIEW OF THE SPACE MISSION DESIGN PROCESS

The majority of space missions are designed in two distinct phases, the conceptual phase and the implementation phase. In the conceptual phase a design is prepared for customer approval, either through a proposal process or as a sponsor-funded study. Conceptual designs are typically developed to some limited level of engineering depth, as specified by some stated need for accuracy of estimated cost and schedule. They are usually inspired by a set of science or technology goals. A traditional approach to concept development would begin with the assembly of a design team, who, through a series of regular meetings or work sessions, dissects the goals into system requirements on hardware, software, operations teams and the like. These are given to designers, who may spend several weeks developing designs and providing cost information. Costs may be grass roots (developed by the designers based on costs of parts and labor), parametric (developed through a software model that uses cost of past designs as a basis and estimated from some design parameters that historically drive cost), or both.

Conceptual designs are incorporated into a proposal submitted to the sponsor for evaluation. If the design is sound and the cost acceptable, the winning proposer is awarded the job and implementation, the second design phase, begins.

As in the conceptual phase, implementation-phase designs are driven by requirements derived from goals. In the implementation phase, however, some method of managing and controlling requirements is necessary, as there are usually frequent updates. Traditionally, system requirements are captured and held in a set of documents which are parsed into increasingly lower level requirements until they are at the level where a single engineering team can design to them. As the design

proceeds, requirements are either accepted or modified, and designers proceed to implement the design as soon as all requirements are accepted. This process involves testing hardware and software as it is developed, and it concludes with the integration of all elements into a whole for final testing and launch of the mission. Testing the system as a whole is seldom successful the first time, and both design errors and fabrication errors are uncovered and returned to the appropriate designer or fabricator for rework. The last and generally most exciting phase of the mission is operations, where the system is used to carry out the science or other goals, and data are returned and analyzed.

This basic design scheme has been used for many space missions for many years and has produced many successes. However, recent pressure to make the design process faster, better, and cheaper has inspired revolutionary changes. Among these are process-based organization, model-based design [3,4], revised leadership and training, and system modeling [2,4,5,6]. Concepts already in use in industrial systems design have also been adopted for use in space missions. In particular the concept of concurrency has received attention as a significant time saver in teams [7,8,9,10,11].

Effectiveness of teams and their relationship to the surrounding organizational culture have been discussed in many environments [e.g., 12,13,14]. Methods to measure and increase innovation in teams are reviewed in [15], and specific metrics for innovation are available [16,17]. The design and measurement of teaming relationships are shown to be an important subject when improving efficiency of a human or human-machine combined process.

THE CONCEPTUAL PHASE DESIGN PROCESS

Traditionally, small, dedicated design teams produce conceptual studies. Each proposal is produced by a unique team that develops and implements its own unique process. Typically the teams meet weekly to report status, review action items, and establish new actions and deliverables. However, the emphasis on different aspects of the design/proposal differs among the teams (e.g.,

cost/performance trades, ground systems/operations concepts, mechanical design, electrical design), as does the analytical tools employed to address these issues. Furthermore, since each team member serves on only one or a few such teams, there is little opportunity to apply lessons learned and little incentive to develop tools and methods that could improve the capabilities of future proposal teams. In addition, since the teams are usually funded with internal development funds, resources are not available to develop new tools or tools that could integrate the outputs of each discipline represented on the team. As a result, analytical efforts are disjointed and not integrated with cost estimates, which are usually attempted only after the primary design variables have been specified.

Thus, both the cost and quality of the proposals generated by this process are highly dependent on the team membership, especially the team leader. Some proposals might be of very high quality, others not. The principal characteristics of this approach are as follows. First, a dedicated, self-sufficient team designs each project from the ground up. Each product is, therefore, unique and has the quality of being produced by hand. Second, approaches to the concept definition, the work breakdown and cost breakdown structures are likewise unique. Third, the tools used to define missions are unique and often generated explicitly for each mission. For example, a mission concept requires study of the trajectory by which a spacecraft may travel to its destination. Some trajectory options will allow a more massive spacecraft, while others may feature a shorter transit time. Software tools are required to discover options, compare them, and optimize them. Similarly, spacecraft subsystem tradeoffs require tools to manage the comparison of more powerful options against less massive ones.

In 1994, in recognition of the nation's changing economic and strategic environment, JPL undertook a re-engineering of our project and system engineering processes [18]. The fundamental nature of the change was from a design-to-performance methodology to one of design-to-cost, but the re-engineering team also described other desirable shifts. Those applicable to concept-phase studies are shown in Table 1.

Table 1. Changes to the Conceptual Design Process (adapted from [18])

FROM	TO
Performance-driven design	Cost-driven design
Sequential design	Concurrent design
Hierarchical process	Consensus process
Deferred problem resolution	Real-time problem resolution
Paper data exchange	Electronic data exchange
Stand-alone tools	Integrated tools
Limited design-space exploration	Comprehensive design-space exploration
Zero-width interfaces	Zones of interaction
Requirements-driven approach	Hardware (capabilities)-driven approach
Subsystem engineering models	System engineering models

Results have been (1) the creation of an environment and a team to apply multidisciplinary design optimization, with full consideration of schedule, mission operations, and cost; (2) the ability to use consensus process for real-time problem resolution; (3) the creation of a set of linked tools that facilitate concurrent design by passing pertinent parameters quickly from one member to all others and eliminate the re-entry of designs between design tools; and (4) the use of cost models to quickly demonstrate the

fiscal effect of major design changes while still in the concurrent environment.

The environment created for conceptual design differs from the traditional environment in a number of ways. The physical environment, called the Project Design Center or PDC, is designed so that engineers can work in a meeting room at the same time that they work in a more private office (Figure 1).

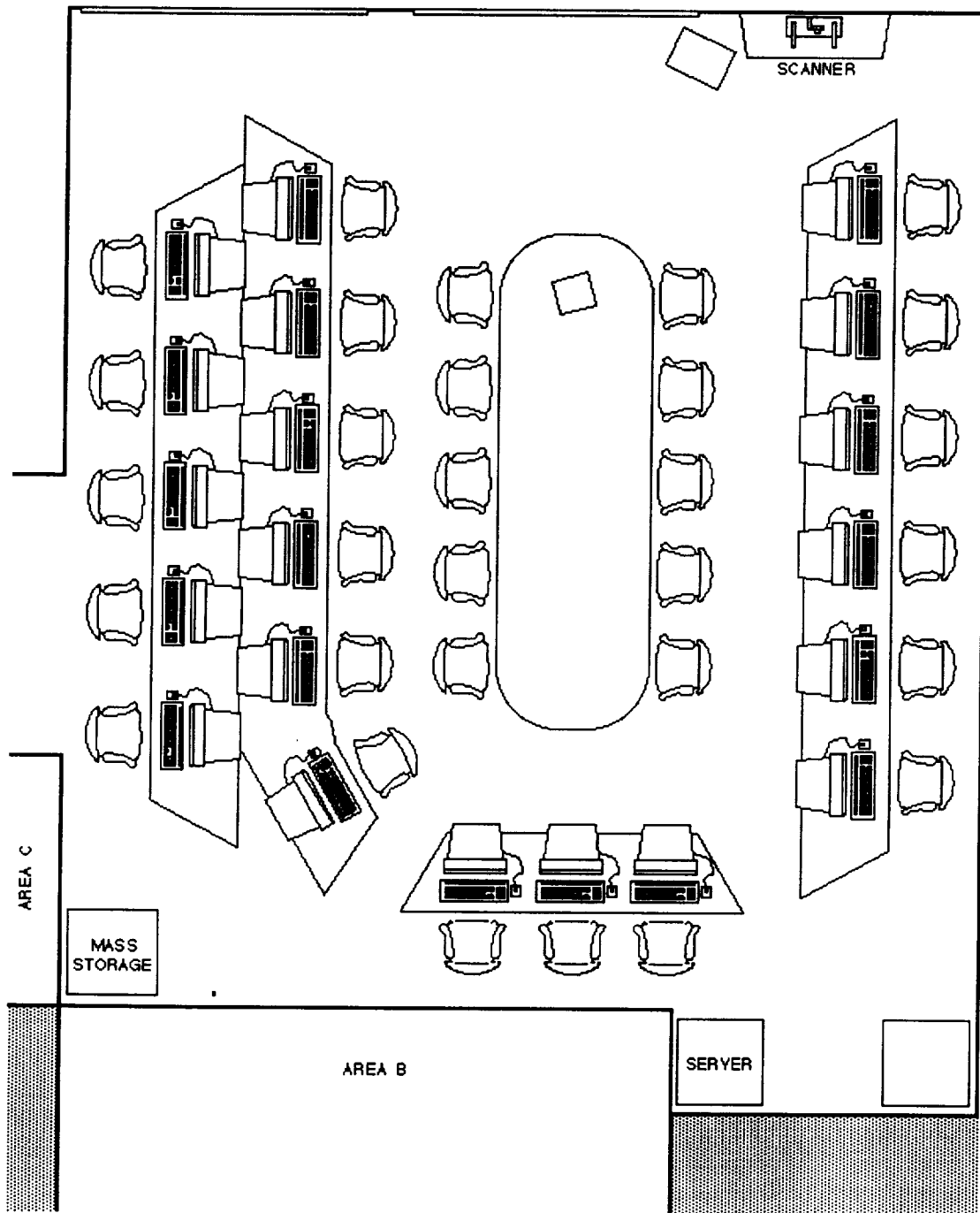


Figure 1. The Project Design Center Physical Layout

In the room are sixteen seats, each occupied by an individual responsible for a particular functional element

of the design, a related programmatic function, or a support function (Table 2). A long table, at which

customers and sponsors sit and discuss design details with members of the design team, occupies the center. Team members are only a 180-degree chair turn away from a workstation and telephone at which they can access any tool necessary for his or her design work. At the front of

the room are three projection screens on which any of the workstations screens can be shown, or on which remote sites can be seen, or on which summaries of the state of the design can be reviewed.

Table 2. Team X Positions

Team/Study Leader	Science	CDS
Systems	Cost	ACS
Power	Telecom-Hardware	Mission Design
Thermal	Telecom-Systems	Propulsion
Structures	Ground Systems	Graphics Design
Programmatics	Instruments	Documentarian

Engineers' workstations are networked to each other using an interconnected system that supplies latest design data to them as the design and the related conversations about the central table mature in concert with each other. In this environment, a team that is also significantly different operates. The Advanced Projects Design Team, universally called "Team X," was formed from members of JPL's technical staff who had participated in previous space mission design and in the missions themselves. Functional design elements common to space missions are each represented by an engineer and a backup. Cost is included as a primary design element. A study leader orchestrates discussions, and a documentarian is responsible for capture of design trades made, rationales for direction, etc. Individuals assigned by JPL program offices, who are considered a customer to whom the service is provided, bring new mission concepts to the team. Team X participates in three-hour concurrent engineering sessions with the study manager to develop the concept to a level of detail sufficient to proceed with a formal proposal. The customer meets with the study leader to define the basics of the idea (e.g., target body, cost target, scope of the design effort, risk philosophy) sufficiently to allow some preliminary homework to be done.

Next, sessions are held with the full team. Team X sessions start with a description of the science objectives and how they might fit into the perceived opportunity. Through discussions with the customer, design team members derive a set of mission requirements that will meet the mission objectives as well as possible within cost. Although each study will vary, a typical Team X session might proceed as follows. The session may begin with a team estimate of spacecraft mass and propulsion requirements appropriate to the mission type based on prior experience. Scientific observation objectives are established (e.g., images to be taken, samples to be returned), and an instrumentation complement is defined. Acquisition data rates are totaled for the instruments. An instrument pointing control requirement is determined and passed to the attitude control engineer. A data collection strategy is derived from the measurement objectives, and acquisition data rates are determined. A data return strategy is worked out and required onboard

data storage is determined. After telecommunications antenna size and pointing control requirements are calculated, the attitude control system (ACS) is sized and the ACS propellant requirement determined. Onboard computer requirements are collected and a data system is chosen.

As the various required functions are defined, preliminary allocations are made to functional elements (although the importance of correct/final functional allocation is restricted to the development of a target cost). Prototypical subsystem components (star scanners, computer processors, propulsion systems and the like) are chosen by the team consistent with the risk philosophy. Component masses and power requirements are totaled by the spreadsheet. For each component chosen, a technology readiness level (TRL) is assigned based on the maturity of the component development at the estimated launch date. Calculated power requirements are used to size the power system, and the thermal control system is defined. The refined spacecraft dry mass total is then used to calculate required propellant mass. A packaging approach is discussed and a drawing of a possible spacecraft structure is produced. The total mass and volume requirements are used to make a final choice of launch vehicle.

The information system engineer prepares a preliminary mission operations concept. At this early stage, the operations concept will be very high level and contain many assumptions. Developing the mission operations concept early in the study phase enables the minimization of life cycle costs as well as the determination of the effectiveness of using existing system capabilities. The earlier the mission operations concept is developed, the more leverage there is for influencing the operability of the entire mission system, including the space element. The development of the mission operations concept is most beneficial when done in parallel with the spacecraft design and there is a tight coupling between the two efforts.

An appropriate parametric cost model is chosen for the class of mission, and selected requirements that have traditionally been strong cost drivers are fed to it. The cost model quickly produces an estimated cost and an

estimate of the uncertainty in that cost based on the TRLs and other factors. This cost estimate is used to iterate design requirements and, if necessary, mission goals until the cost goal is met. Similarly, mass or power totals can be quickly iterated against a fixed cost, launch vehicle, or other fixed requirement. Importantly, broad trade spaces involving ground equipment, flight equipment, science objectives and cost can be addressed in the concurrent environment. Infusion of new technology can be balanced against anticipated schedule and cost impacts. After an agreement is reached on a design point each design engineer can provide a grass roots estimate of the cost of his or her function. Those estimates are totaled, and deviations of the grass roots cost from the modeled cost are then reviewed and justified.

Team X sessions are summarized by the team members and the documentarian into a final report during the session itself, using a distributed word processor available to all positions. The final form of the design is captured in the report and into a database for later recovery. Text from the final report is made available to the customer for preparation of a proposal.

CONCEPTUAL PHASE METRICS

Team X has been in existence for over three years and is now an established part of our conceptual phase design

process. Figure 2 shows the related metrics. Previously, JPL had been able to complete at most ten conceptual designs in one year, requiring 26 weeks to complete and at a typical cost of \$250k. With the revised process, engineering designs for more than fifty mission concepts per year are generated in less than two weeks each, requiring total funds less than \$75k. In 1996, 45 such designs were completed; in subsequent years this number was increased to 50 to 75, often requiring two instances of Team X operating in parallel. This increased capacity has been used to enable the creation of candidate mission roadmaps, allowing NASA to choose among proposed mission sets rather than single missions. Some of this time saved is that previously required to assemble a team, relieve them of other duties, establish procedures, and other bureaucratic necessities, but other efficiencies have come from shortened communication loops, computer-to-computer data exchanges, and online report writing. An additional advantage is that the Team X approach has enabled design cycle times measured in minutes or hours rather than weeks. Thus the option exists to allow much broader design space exploration and optimization if desired.

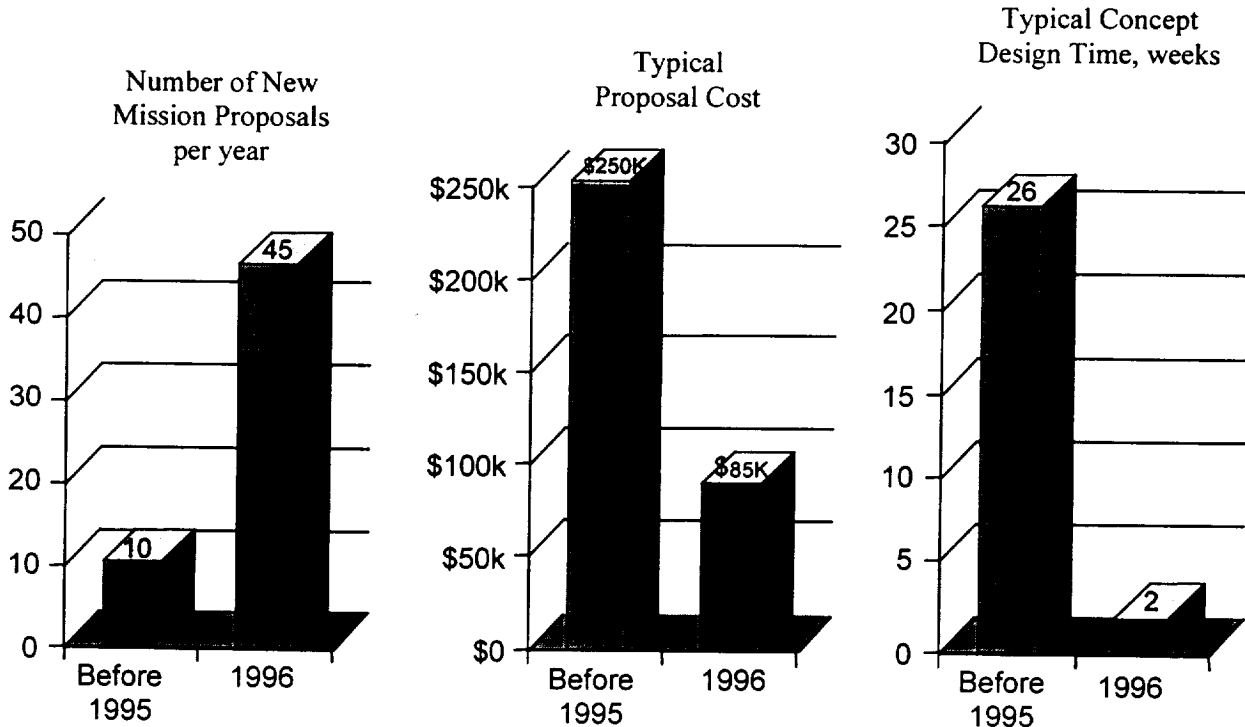


Figure 2. Conceptual Phase Design Metrics

IMPLEMENTATION PHASE DESIGN

Most of the actual design work is done following acceptance of a mission, in the implementation phase. Compression of this design process has also received attention in the past few years. Tools and tool linkages

that compress this phase are discussed in [1] and [2], and an overview of a redesigned process has been elaborated in [5].

We have implemented and are evaluating such a system for implementation phase design, with the teaming outline

and database structure shown in Figure 3. In this scheme, high-level mission constraints are defined by the mission team using the conceptual design described in the previous section of this paper. The mission team includes such roles as the project scientist, mission engineer, and flight and ground system engineers. These are captured in the timelining tool APGEN [20] as rule-based statements of events that must happen together, must not happen together, must follow each other, etc. The team

loads rough estimates of power, data, and other resources into APGEN for each event. Mission science teams and mission designers create a mission scenario that describes in high-level terms what activities a mission is to accomplish in APGEN. The program captures the timeline and, given the resource estimates, makes plots of resource usage as a function of time. A mission scenario that is roughly consistent with constraints and resources is output from APGEN.

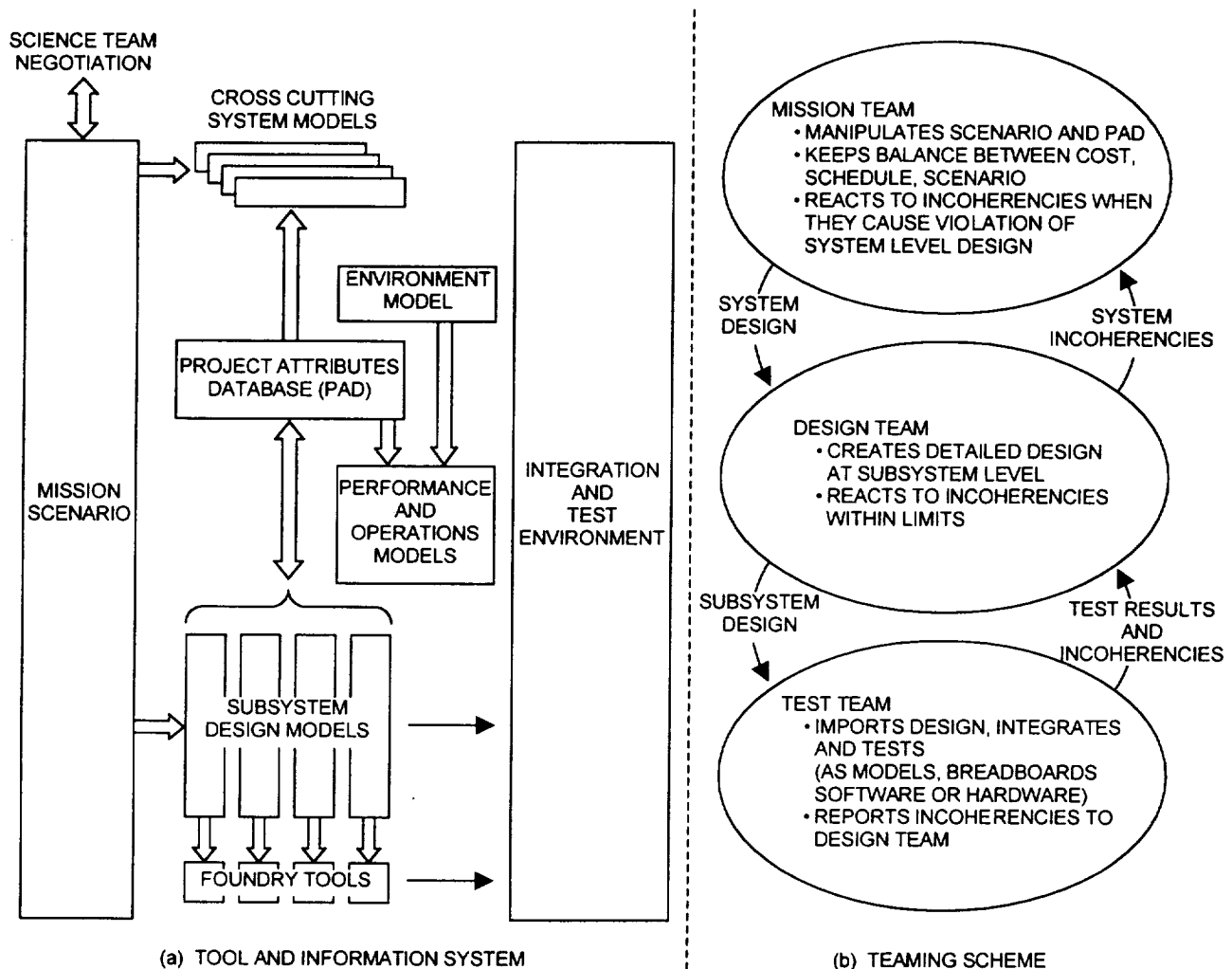


Figure 3. Data and Teaming Flow for Implementation

The conceptual design and mission scenario are used to create high-level system requirements and a system design, which are stated in modeling software following [4]. Parameters describing the design are revised from the conceptual design and stored in a central database called the Project Attributes Database (PAD). Parameters are linked to system models, and a product breakdown structure is created that attaches system level parameters (e.g., system mass, cost, and power) to subsystem parameters (e.g., individual subsystem masses, costs, and power). The system models are then attached to the APGEN output and executed to ensure that the scenario can be executed by the designed system. For example, power requirements and power sources are balanced with

battery capacity, data sinks and sources are balanced against onboard storage capability and data downlinks, and the like. Note that cost and schedule are regarded as system models and are estimated and balanced like any other engineering parameter. The cost model, for example, may be a parametric model based on past missions that uses some parameters from the PAD to continuously update both life cycle cost and cost profile by year as the design cycle proceeds, or it may be a combination of parametric and grassroots methods as in the conceptual phase.

When requirements and scenario are in balance, the mission team's attention shifts to the scenario as

subsystem design begins. First, constraints are refined in APGEN in response to the capabilities of the system design. Then the mission scenario is updated and sufficient detail is added to make the scenario useful as a source of test procedures.

To begin subsystem design, the mission team releases the design to the design team, whose job it is to design the subsystems required in the system design. Design parameters and resource allocations are extracted from the PAD and models more behavioral in nature are created of subsystems. In the PAD, a set of parameters parallel to the system design specifications is created so that subsystem design values can be entered for comparison. In addition, the number of parameters is expanded to include subsystem designs, some of which will have no system equivalent. Subsystem models are delivered to the test team, who operates in the system integration and test environment to integrate the modeled subsystems and test them. The test team uses test procedures drawn either from requirements or from the mission scenario to test these models in the first instance of system test (which in the previous paradigm does not occur until much later). For each test cycle, another parallel set of parameters is created in the PAD to represent actual measurements. Test results are used to discover test failures or "incoherencies," which are returned to the design team for design correction. If the design team is unable to resolve the incoherency within the allocations present in the PAD, the incoherency is returned to the mission team. For example, a subsystem engineer in the design team may find that the design requires more power than anticipated, and that there is no solution within that subsystem—this is known in the trade as a "design pushback" on requirements. Such incoherencies are treated as an imbalance in the system models and resolved by readjusting the scenario, rebalancing the system level requirements, or both. Note that in this rebalancing cost and schedule are continuously updated and obvious, and can thus be treated as independent variables.

The cycle described above is repeated as new system designs translate into new constraints, scenarios and subsystem designs. As the design matures, subsystem models of designs are replaced by breadboards and flight or ground hard- and software, and the test environment proceeds from testing of models through testing of hybrids of models/breadboards/hardware to final test of flight and ground equipment. Thus final integration and test becomes simply another in a series of integrations which lead from models to flight and ground hardware and software. Although unproven, our expectation is that design errors will be uncovered much earlier as the models are tested together, and final integration and test will be able to concentrate on the discovery of fabrication errors, thus reducing the number of redesigns required.

Imbalances at the system level can, and often do, occur for external reasons. The mission sponsor sometimes directs the project to reduce its life cycle cost or readjust costs by year. The science team may respond to recent

scientific results or other needs by changing the scenario, or new findings about the environment (radiation levels, for example) may make the mission's task different in some way. Whereas past philosophy has been to resist such changes (freeze the requirements), experience has shown that they are common and probably inevitable. In our proposed scheme, at each rebalance by the mission team (which can be brought on by either a new system design or a new scenario or both) the latest updates from both system and scenario are used, thus accommodating changes to either. Similarly, management reviews are accomplished by witnessing the satisfaction of the scenario by the system models.

In summary, we expect four major advantages of this scheme over traditional design practice. First, the use of three concurrent teams provides a naturally shorter design cycle. Traditional schemes have design cycles limited by weekly meeting schedules, interspersed with manual (telephone, e-mail or paper) data exchanges. This scheme's concurrent teams do not need weekly meetings, and they exchange data through the PAD, enabling design cycle times measured in days. Second, the enabling of fluid requirements encourages creative solutions that reach outside of existing requirements and allow more trade-space exploration during detailed design. Third, more fluid requirements will allow and account for both sponsor-inspired changes and subsystem design pushback. Finally, the use of models allows early system test and design error detection, saving rework and reserving final integration and test time for discovery of fabrication errors. In the conceptual design phase we have also noted increased employee satisfaction, higher team innovation and more team loyalty, and we expect similar advantages in the implementation phase designs as well.

CONCLUSION

This paper describes two new processes for space mission design. The revised processes involve fundamental changes in the integration of design tools, the design process, and the team structures. In the conceptual design phase, a facility that promotes concurrent engineering incorporates linked design tools and redesigned process featuring management of team discussions. This new process has resulted in significant favorable changes in design time, cost and quality. A proposed change to the design scheme in implementation phase design has potential for similar improvements in time and quality.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

- [1] Smith, D. B., "Reengineering space projects," *Computer Tools, Systems Engineering and Competitiveness Symposium*, March 5-7, 1997.
- [2] Wall, S., Baker, J., Krajewski, J., and Smith, D., "Implementation of system requirements models for space

- missions," *Proceedings of the Eighth Annual International Symposium of the International Council on Systems Engineering*, July 26–30, 1998.
- [3] Hammer, M. and Champy, J., *Reengineering the Corporation*, New York: Harper Business, 1993.
- [4] Baker, L., Clemente, P., Cohen, B., Permenter, L., Purves, B., and Salmon, P., "Foundational concepts for model driven system design," *Proceedings of the INCOSE Model Driven Systems Design Working Group*, 1997.
- [5] Smith, D. and Koenig, L., "Modeling and project development," *Proceedings of the Fifth International Workshop on Simulation for European Space Programmes—SESP '98*, November 1998.
- [6] Barbieri, A. and Estabrook, P., "System models to reduce mission design time and manage risk: the Mars Microprobe Mission case study," *Proceedings of the Twelfth AIAA/USU Conference on Small Satellites*, 1997.
- [7] Corbett, J., "Design for economic manufacture", *Production* 99,7, 36–1, 1987.
- [8] Cohodas, M. J., "Make the most of supplier know-how," *Electronics Purchasing* 38–9, 1988.
- [9] Dunn, J., "Side-by-side to success," *The Engineer*, 11 October 1990.
- [10] Clark, K. B., and Fujimoto, T., "Overlapping problem solving in product development," Harvard Business School Working Paper 87-049, 1987.
- [11] Clark, K. B., and Fujimoto, T., "Lead time in automobile product development; explaining the Japanese advantage," Harvard Business School Working Paper 89-033, 1989.
- [12] West, M. A., *Effective Teamwork*, Leicester: British Psychological Society, 1994.
- [13] Schnieder, B., ed., *Organizational Climate and Culture*. San Francisco: Jossey-Bass, 1990.
- [14] West, M. A., "The social psychology of innovation in groups," in *Innovation and Creativity at Work* (West and Farr, eds.) New York: John Wiley and Sons, 1990.
- [15] Hoskings, D. M. and Anderson, N. R., *Organizational Change and Innovation*, London: Routledge, 1992.
- [16] Anderson, N. R. and West, M. A., "Measuring climate for work group innovation: development and validation of the team climate inventory," *J. Org. Behavior* 19, 235–258, 1998.
- [17] Anderson, N., and West, M. A., "The Team Climate Inventory: development of the TCI and its applications in team building for innovativeness," *European Journal of Work and Organizational Psychology* 5(1), 53–66, 1996.
- [18] Casani, K., "Reengineering the JPL Project Design Process," *JPL Internal Document D-11785*, 1994.
- [19] Koenig, L., Smith, D., and Wall, S., "Team efficiencies within a model-driven design process," submitted to *Ninth Annual International Symposium of the International Council on Systems Engineering*, 1999.
- [20] Maldague P., Ko, A., Page D. and Starbird, T., "APGEN: A Multi-Mission Semi-Automated Planning Tool," *International Workshop on Planning and Scheduling for Space Exploration and Science*, 1997.